Propagation and Directional Scattering of Ocean Waves in the Marginal Ice Zone and Neighboring Seas

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LONG-TERM GOALS

This project is designed to better understand the sea state and boundary layer physics of the emerging Arctic Ocean, by addressing aspects of the first three points in the ONR DRI on *Sea State Boundary Layer Physics of the Emerging Arctic*, i.e.

1. Identify and parameterize factors affecting the spatial and temporal variability of sea state, and improve forecasting of waves on the open ocean and in the marginal ice zone;
2. Develop an improved theory of wave attenuation/scattering in the MIZ sea ice cover;
3. Use wave scattering theory directly in an integrated Arctic system model, and include ice floe bending and fracture, for use in Arctic system models.

OBJECTIVES

1. To contribute to the collection of field data.
2. To develop an efficient operational wave-ice numerical model.
3. To add value to the research already funded as part of the Sea State DRI.

APPROACH

We propose to revisit the Perrie and Hu (1996) formulation. There are several tasks that need to be done. For example the scattering kernel needs to be investigated. While we understand how to calculate the scattering kernel for given *single* ice floe properties, it does not make sense to apply this directly into an operational model. This is because if only a single floe property is considered there may be strong resonances. Therefore, to capture wave-ice interactions in the general MIZ case (Fig. 1), the kernel should be calculated by simulating and averaging a range of floe properties. Once this simulation has been done, it may actually lead to a simplification of the scattering kernel. This is because the average kernel will only depend slowly on variables such as period or floe size. Put simply, after averaging is completed, the kernel for a period of 11 s can be expected to be the average of the kernel for 10 s and 12 s. This means that we should be able to calculate empirical formulas for

the scattering kernel which will make calculation of the kernel in the ocean wave models very quickly. Floe flexure and breaking need to be considered.

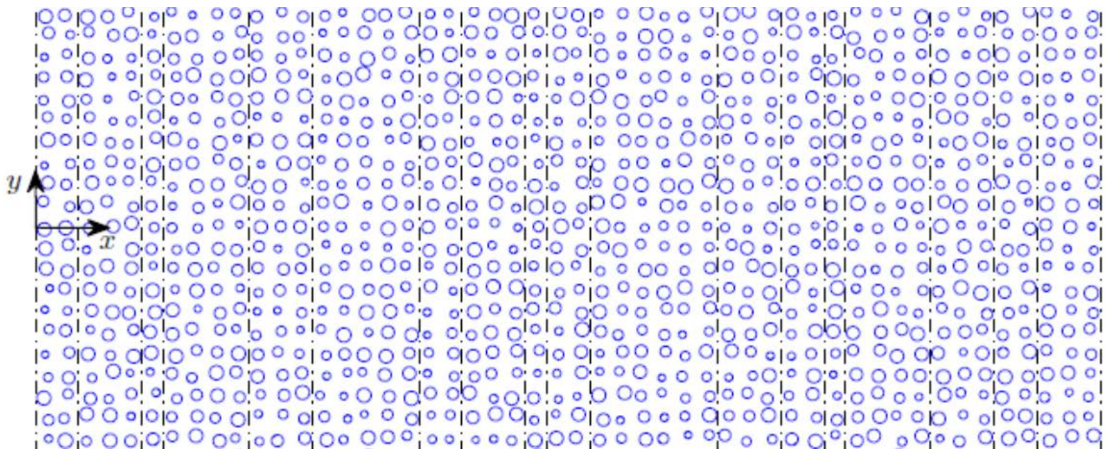

Fig. 1. An example of the massive floe simulation test of Squire et al.

In our test simulations, the MIZ can be subdivided into N adjacent infinite strips of specified finite width (Fig. 1), composed of a finite random array of circular ice floes with positions, radii, and thicknesses uniformly distributed within the regular array. Thus, test cases may consist of various spectra generated by WW3, with (assumed) constant wind, say 20m/s to the east (right), and angular spreading specified by WW3; the waves then attenuate, reflect at the ice edge, or scatter as they propagate through the MIZ.

Comparisons need to be validated with *in situ* and remotely sensed observations. Details are:

(A) Wave-ice Model development

i. *Wave model*: Transition the methodology of Perrie and Hu (1996) to the state-of-the-art for operational wave forecasting, for example WW3, version 4.18. Incorporation of the scattering term in modern ocean wave models requires some pre-calculations of the scattering kernel.

ii. *Elastic ice floes*: Use the elastic plate model for ice floes and the updated elastic scattering kernel formulation of Meylan and Masson (2006). This will establish a way to incorporate the scattering terms into modern wave models such as WW3.

iii. *Multiple scattering*: Test the effect of multiple scattering and relatively dense floe packing. Thus, establish a way to incorporate what has been done by Squire and co-workers into the wave model paradigm (in which the phase of the wave is not resolved).

iv. *Floe breaking*: To be simulated by setting a floe breaking criteria based on significant wave height and then modify the scattering kernel as part of the time-stepping.

v. *Academic tests*: Perform (SWAMP-type) tests that include hypothetical constant winds with simple geometry ocean topography, described in the previous section.

vi. *Real storm tests*: Implementation WW3, with wave-ice interactions code implemented, in the Arctic, or where there is high-quality ice-ocean data, for tests with *real storms and high waves*. Perform *in conjunction* with other available DRI waves-in-ice models.

vii. *Validation*: We can validate wave-ice scattering / attenuation model by comparisons with *in situ* attenuation rates, and collocated satellite remotely sensed imagery collected from the field experiments:

a) BLSS DRI field experiment deployed in 2015.

b) MIZ DRI deployment of *in situ* arrays in 2014 in the Beaufort Sea.

c) The R/V Oden cruise along 'the Northern Route', in 2014.

Thus, we propose to use this model system to link to the phase resolved simulations of other available DRI waves-in-ice models.

(B) *Remote sensing observations* need more investigation for the MIZ. Relations that apply to open ocean conditions cannot be assumed to still apply in MIZ waters. Details are:

i. *SAR Wave retrievals*: Develop improved techniques for wave spectrum retrieval from SAR in the MIZ, building on recent developments.

ii. *Wave transformations*: Conduct studies of wave pattern changes when waves penetrate into the MIZ, using SAR data.

iii. *Wave dissipation*: Develop a methodology to retrieve wave energy dissipation rate from SAR, as a function of ice parameters, such as ice floe size, ice floe draft, ice cover concentration, etc.

iv. *Spectral partitioning*: Based on wind speed, wave age and altimeter backscatter data (from HY-2), develop a method to partition wind-sea and swell contributions to local MIZ wave spectra.

v. *Swell in MIZ*: Investigate swell energy propagation into ice, and obtain dissipation rate for swell, based on SAR observations.

vi. Wave attenuation: methodology to estimate wave attenuation in the MIZ from SAR images, for a variety of wave and ice conditions.

vii. *Validations*: Conduct comparisons of SAR data collocated with *in situ* data from field experiments, showing growth, and development of wave spectra, attenuation, scattering, reflection, etc. as waves propagate into the MIZ.

WORK COMPLETED

A. **Wave-ice Model development**

i. *Wave model*: We are presently making the code conversion to transition the methodology of Perrie and Hu (1996) to the state-of-the-art for operational wave forecasting, specifically, WAVEWATCHIII (WW3), version 4.18. This involves incorporation of the scattering term in modern ocean wave models requires some pre-calculations of the scattering kernel.

ii. *Elastic ice floes*: We have developed implementation plans for using the elastic plate model for ice floes and the updated elastic scattering kernel formulation of Meylan and Masson (2006), in order to establish an incorporation of the scattering terms into WW3.

iii. *Multiple scattering*: We have developed implementation and test methodologies for multiple scattering and relatively dense floe packing test cases, in order to incorporate related work by Squire and co-workers into the wave model.

iv. *Floe breaking*: We have developed implementation and tests to simulate floe breaking based on significant wave height, using the scattering kernel as part of the time-stepping.

v. *Academic tests*: We have developed set-ups and completed some runs for (SWAMP-type) tests that include hypothetical constant winds with simple geometry ocean topography.

vi. *Real storm tests*: While waiting for the October 2015 field work to be completed, we have set-up the model for simulations of the test cases observed by Kohout et al. (2014) in Antarctica.

vii. *Validation*: We are planning validation tests for wave-ice scattering / attenuation model by comparisons with *in situ* attenuation rates, and collocated satellite remotely sensed imagery collected from the field experiments:

a) DRI field experiment deployed in 2015.

b) The R/V Oden cruise along 'the Northern Route', in 2014

c) Test cases observed by Kohout et al. (2014) in Antarctica.

(B) **Remote sensing observations**

a. *SAR Wave retrievals*: We have developed improved techniques for wave spectrum retrieval from SAR in the MIZ, building on recent developments.

b. *Wave transformations*: We have conducted preliminary studies of wave pattern changes when waves penetrate into the MIZ, using SAR data.

c. *Wave dissipation*: We have developed a preliminary methodology to retrieve wave energy dissipation rate from SAR, as a function of ice parameters, such as ice floe size, ice floe draft, ice cover concentration, etc. More data is always welcome.

d. *Swell in MIZ*: We have completed a preliminary study of swell energy propagation into ice, and obtain dissipation rate for swell, based on SAR observations.

e. *Wave attenuation:* We have developed a methodology to estimate wave attenuation in the MIZ from SAR images, for a variety of wave and ice conditions. More data and *in situ* validation is always welcome.

f. *Validations*: We hope that the DRI field experiment in October 2015 will yield comparisons of SAR data collocated with *in situ* data, showing growth, and development of wave spectra, attenuation, scattering, reflection, etc. as waves propagate into the MIZ.

RESULTS

The meaningful technical results achieved in the report fiscal year are the comparisons of wave attentuation from SAR imagery in the Greenland Sea, suggesting results that appear to be consistent with wave attentuations found by Kohout et al. (2014). This is signifcant because *in situ* field experiments are expensive and difficult to perform. This is a "new capability".

IMPACT/APPLICATIONS

If remote sensing observations from SAR (Synthetic Aperture Radar) can be shown to reliably measure wave attentuation and scattering in the MIZ, for example from RADARSAT-2, then there is potentially much more data available to inform models and to lead to improvements in model skill for simulations and predictions.

RELATED PROJECTS

The Canadian Panel on Energy Reserch and Development has funded Perrie to do Arctic studies of storms, and coastal processes in the Beaufort and Chukchi Seas, of relevance to oil and gas exploitation. This project also involves wave-ice interactions in the marginal ice zone, MIZ.

REFERENCES

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PUBLICATIONS

Shen, H., W. Perrie, Y. Hu, Y. He, S. Li: 2015: Remote Sensing of Waves Propagating in the Marginal Ice Zone. *Geophys. Res. Lett.* [Submitted, refereed].